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Ensemble Prediction of Brown Planthopper, *Nilaparvata lugens*, Overwintering Area under Future Climate Conditions

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SEMI LEE

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ABSTRACT

The brown planthopper (BPH), *Nilaparvata lugens* (Stål), is an insect pest in rice paddies across the East Asia. Because BPH cannot survive under low temperature conditions (<12 ℃), it migrates from the tropics to temperate areas with severe winter conditions. The objective of present study was to assess potential areas for BPH overwintering in East Asia under current and future climate conditions. To predict potential overwintering areas of BPH, 176 occurrence sites, which include 88 favorable sites and 88 non favorable sites for overwintering, were obtained from literatures. Two sets of climatic variables including temperature and precipitation were used to represent temperature and humidity conditions in paddies, which are key environmental factors for overwintering of BPH. Current and future climate maps of these variables were used as inputs to species distribution models (SDMs). Five SDMs including ANN, BIOCLIM, GARP, MAXENT, and SVM were used. To reduce model uncertainty, we explored an ensemble modeling approach using multiple sets of SDMs and climate data. Climate data which were averaged over the period from 1960 to 1990 were used for current climatic conditions. Future climate data generated from five general circulation models (GCMs) with an emission scenario of A1B were used for BPH overwintering distributions in 2020s and 2050s. For future predictions, outputs of each SDM were generated using five sets of climate data from general circulation models (GCMs) and averaged into a single map. The single map was classified as presence and absence by the threshold of 0.5 for each SDM. The optimum ensemble method was applied to predict future geographical distribution of BPH overwintering area. From predictions in this study, the northern limit of BPH overwintering suitability shifted north by 100-200 Km in most regions in East Asia in the next 40 years. Therefore, future studies in monitoring migration routes of BPH are considered to be important.

Key words: *N. lugens*, rice pest, overwintering region, SDM, ensemble method, climate change

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LIST OF ABBREVIATIONS

BPH:	Brown Planthopper
SDM:	Species distribution model
ANN:	Artificial Neural Network
GARP:	Genetic Algorithm for Rule-set Prediction
MAXENT:	Maximum Entropy
SVM:	Support Vector Machine
K:	Kappa value
En #:	Ensemble prediction having agreements from a given numbers of models (#)
TT:	A set of temperature related variables
TP:	A set of temperature and precipitation variables

INTRODUCTION

The brown planthopper (BPH), *Nilaparvata lugens* (Stål), has caused serious problems in rice production in Asia (Dyck and Thomas, 1979; Sogawa and Cheng, 1979; Kisimoto, 1979; Turner et al., 1999; Zhu et al., 2000). Both nymphs and adults of *N. lugens* suck the plant sap, which may cause a hopperburn and death of the plant (Rosenberg and Magor, 1983; Kisimoto and Sogawa, 1995). BPHs also transmit pathogens of rice ragged-stunt, rice grassy-stunt and rice wilted-stunt to threaten the host plant (Dyck and Thomas, 1979; Rosenberg and Magor, 1983; Pender, 1994). In temperate regions, BPH colonizes rice paddies in an early season, e.g., from late May to July, whereas it remains in the paddies throughout a year in tropical regions (Kuno, 1979).

The outbreak of *N. lugens* is dependent on biotic and abiotic factors. These factors include the initial density of populations, the growing stage of rice plants, natural enemies of BPH, excessive applications of nitrogen and insecticides, air movement within the microhabitat, and weather conditions (Kisimoto, 1976; Dyck and Thomas, 1979; Kisimoto and Sogawa, 1995; Visarto et al., 2006; Watanabe et al., 2009). In general, temperatures above 30 ℃ and below 8 ℃ are known as unfavorable conditions for BPH survival (Bae and Pathack, 1970). BPH cannot survive during winter in most of temperate regions where the average temperature is lower than 12 ℃ in January (Cheng et al., 1979; Kisimoto and Sogawa, 1995). Therefore, outbreaks of BPH in temperate regions result from long-distance migration from tropical areas (Mochida and Okada, 1979; Rosenberg and Magor, 1983, Turner et al., 1999; Otuka et al., 2005a; Wada et al., 2009).

Potential regions where BPH can overwinter have been proposed using temperature conditions or geographical references (Cheng et al., 1979; Kisimoto and Sogawa, 1995). Cheng et al. (1979) suggested that the latitude of the Tropic of Cancer (23.3 °N) would be the northern limit of the overwintering zones for BPH with variations between 20 ° and 25 °N. In Taiwan where latitude ranges from 22° to 25° N, for example, BPH has been found in the northern areas as well as the central and the southern areas (Chu and Yang, 1985). Kisimoto and Sogawa (1995) suggested the 12 ℃ isotherm as the northern boundary for overwintering of BPH, which includes Okinawa and the southern coastal region of china.

Species distribution model (SDM) can be used to assess potential overwintering region of BPH. A SDM predicts geographical distribution of a species finding the environmental characteristics of species occurrence sites including climate conditions. For example, Zheng et al. (2011) predicted overwintering regions of the beet armyworm in China using the CLIMEX model, which is one of SDMs. Dupin et al. (2011) proposed an approach to predict the western corn rootworm using nine SDMs. A SDM predicts shifts in the geographic distribution of a species under the climate change conditions (Berry et al., 2002; Meynecke, 2004, Thomas et al., 2004). Giannini (2013) projected future distribution of bees and their forage plants in 2050s using MAXENT which is another SDM.

Under climate change conditions, the potential overwintering region of BPH in East Asia could expand northward (Hickling et al., 2006). However, little effort has been made to predict potential overwintering region of BPH using a SDM. Uncertainties would be incurred by predicting geographical distribution of a species under future climate conditions. Polikar (2006) and Zhou and Du (2010) suggested that an ensemble method would reduce uncertainty. For example, Leory et al. (2013) used an ensemble approach with eight ensemble members with two emission scenarios (A1 and B1) and three general circulation models to predict distribution of a spider. The objective of this study was to project geographical shift in BPH overwintering region in East Asia under climate change conditions in 2020s and 2050s. We explored an ensemble method using multiple GCMs and SDMs. Changes in BPH overwintering regions were on focus in the present study because shifted geographical distribution of BPH would have considerable impact on rice production in the future.

MATERIALS AND METHODS

1. Species Distribution Data

Occurrence sites where a species of interest has been reported are required for prediction of geographical distribution of the species using a SDM. In total, 119 sites where BPH has been reported were collected from literatures. When no geographical coordinate was available at these sites, a locality that represents rice paddy within the site was selected from visual inspection using Google Earth (Google Inc. Mountain view, CA). Cheng et al. (1979) proposed that 12 ℃ in January is the threshold temperature of overwinter for BPH. Since January is likely to be the coldest month in a year, 119 occurrence sites were divided into two groups by the threshold. As a result, 88 sites were classified as potential overwintering sites. The remaining 31 sites were used to represent non-favorable sites for overwintering of BPH. 57 pseudo-absence sites were additionally obtained from area where the mean temperature of the coldest is lower than 12 ℃ and rice is not cultivated. In total, 176 occurrence sites, which include 88 overwintering sites and 88 absence sites, were obtained (Fig. 1).

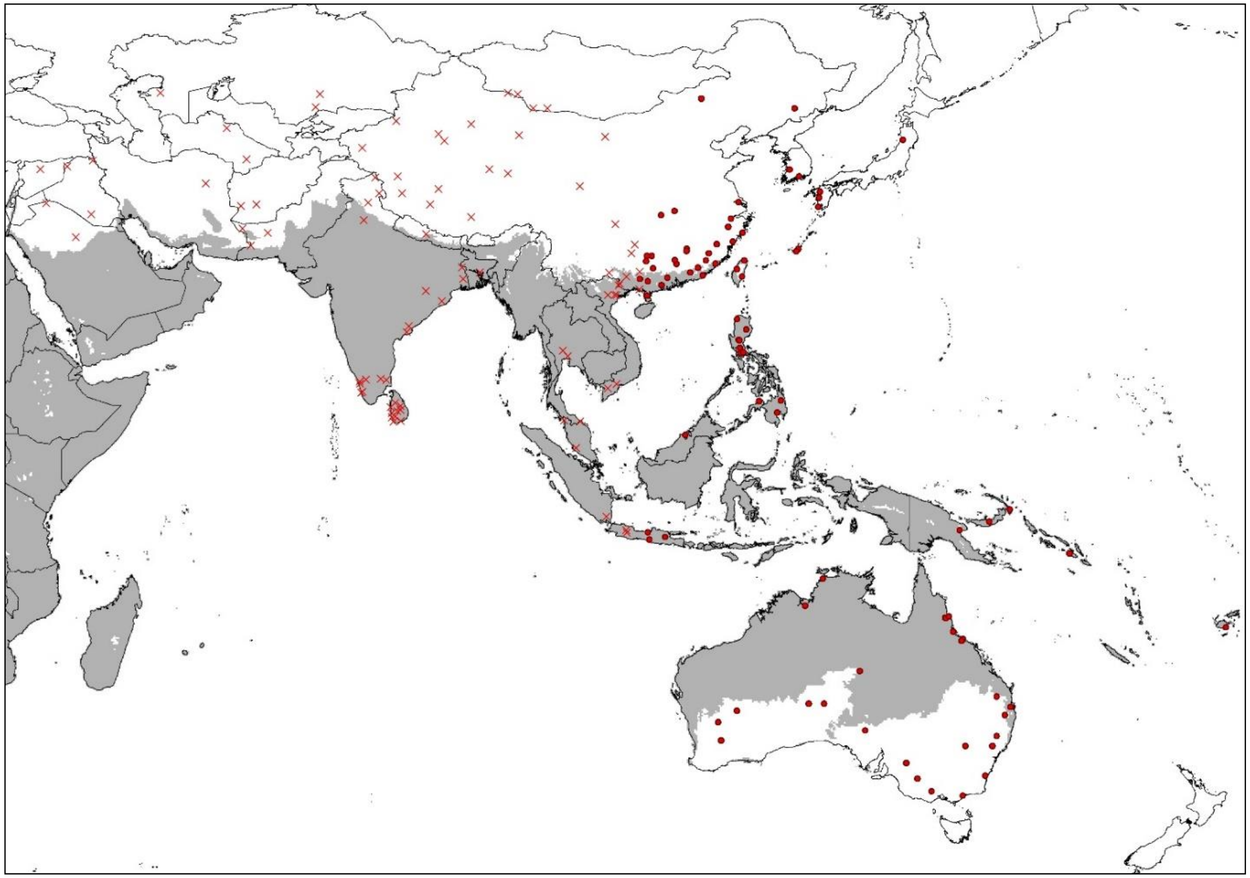


Figure 1. Geographical distribution of 176 BPH occurrence sites. These sites were used for calibration (88 sites) and validation (88 sites). Calibration and validation sites were denoted by circle and cross, respectively.

2. Environmental Data Set

Climate surfaces at low spatial resolution were used to represent climate data of occurrence sites where BPH occurred. It would be preferable to use climate surfaces at low spatial resolution when geographical location of occurrence sites is prone to errors in representing climatic conditions for a given area (Chapman et al., 2005). Because some of overwintering sites were identified from localities within an area, e.g., city or county, climate data at relatively low resolution e.g., 10 arc-minutes (~20 Km^2) were used to obtain climate data at occurrence sites. To predict potential overwintering regions, climate maps at the high spatial resolution, e.g., 30 arc-seconds (~1 Km^2), were used. Climate surfaces for current conditions were obtained from the WorldClim database (http://worldclim.org). For future climate conditions, Climate Change, Agriculture and Food Security (CCAFS) database (http://www.ccafs-climate.org) was used to retrieve climate surfaces.

The current climate surfaces were generated from spatial interpolation of climate data averaged over the period from 1960 to 1990 (Hijmans et al., 2005). Climate surfaces representing 2020s and 2050s (averaged from 2010 to 2039 and 2040 to 2069, respectively) were generated with general circulation models (GCMs) including CCSM3, ECHAM5, CSIRO Mk3, HadCM3 and HadGEM1. The Community Climate System Model version 3 (CCSM3) which was created from NCAR in U.S. is a coupled model consisting of four components e.g., atmosphere, ocean, sea ice, and land surface (Collins et al., 2005). ECHAM5, which has been originated from the institute of ECMWF was modified and further parameterized at Hamburg (Roeckner et al., 2009). CSIRO Mk3 climate system model is a fully coupled ocean-atmosphere system which is assembled from two major modules, i.e., the Atmospheric General Circulation Model (AGCM) and the Ocean General Circulation Model (OGCM) (Gordon et al., 2002). HadCM3 which was developed at the Hadley Centre in the United Kingdom is also a coupled ocean-atmosphere GCM and does not need artificial flux adjustments (Collins et al., 2001). HadGEM1 (Hadley Centre Global Environmental Model version 1) was improved from HadCM3 in terms of higher spatial resolution and interactive atmospheric aerosols and their effects (Johns et al., 2006).

The IPCC SRES A1B scenario, which covers effects of a balance across demographic, economic and technological driving forces and resulting greenhouse gas emissions (Solomon et al., 2007), was selected to prepare future climate data in the present study. Monthly temperature and precipitation as well as bioclimatic variables derived from temperature and precipitation were used as input variables to SDMs.

3. Species Distribution Models

Potential overwintering areas of BPH were predicted using five SDMs, which were implemented in openModeller (version 1.1.0). The openModeller system provides a user interface which makes it easy to run multiple models (Santana et al., 2006; Muñoz et al., 2011). Because a number of models are included in one platform, openModeller makes it easy to compare different SDMs with the same inputs (Peterson et al., 2008; Kumara et al., 2009; Vasconcelos et al., 2012). Each SDM generates georeferenced maps based on the correlative method to represent the environmental suitability for a given species. Five SDMs were used to generate maps with default parameter settings in openModeller to predict overwintering regions of BPH. Below are descriptions of the SDMs used in this study.

Artificial Neural Network (ANN) makes use of training sets to find patterns in the data (Rumelhart et al., 1986; Karul et al., 2000; Lusk et al., 2001; Pearson et al., 2002). Neural networks consist of input layers, output layers and interconnecting artificial neurons. Biological neurons and the networks can process the nonlinear relationships that determine bioclimatic envelopes to predict distributions of species (Pearson et al., 2002).

BIOCLIM makes use of bioclimatic variables (e.g. the seasonality of temperature and precipitation) to predict a region where a species can remain its population. All the parameter values of the bioclimatic variables are obtained from ranges of climatic envelopes from occurrence sites of a given species (Campbell et al., 1999;

Doran and Olsen, 2001; Steinbauer et al., 2002; Walther et al., 2002; Rubio and Acosta, 2010). Because this model runs based on the assumption that species distributions depend on climate, overestimation and misclassification could result from excluding biotic interactions of a species and including unnecessary parameters individually (Beaumont et al., 2005).

GARP with Best Subsets implemented in the openModeller was used. The Genetic Algorithm for Rule-set Prediction (GARP) iterates processes of creating a rule, testing and choosing or rejecting the rule (Stockwell, 1999; Godown and Peterson, 2000; Peterson, 2001; Peterson et al., 2008; Kumara et al 2009). The possible rules are range rules, negated range rules, logistic regression, bioclimatic rules (Robert et al., 2002; Joyner et al., 2010). The GARP with Best Subsets that overlays the selected rule sets was run to predict potential overwintering region of BPH.

Maximum Entropy (MAXENT), which is one of machine-learning methods is based on the assumption that the species distribution is closed to uniform or most spread out (Elith et al., 2006; Hernandez et al., 2006; Phillips et al., 2006; Rubio and Acosta, 2010; Vasconcelos et al., 2012). It builds models starting with the largest spread of species geographical data with regard to a set of background environmental variables. MEXENT is subject to the constraints that the expected value of each environmental variable should match its empirical average (Phillips, 2006).

Support Vector Machine (SVM) is one of non-parametric statistical approaches for classification problems. SVM uses kernel function to map data (presence and absence records) onto a higher dimensional space in which complicated patterns can be more simply represented (Drake et al., 2006; Reiss et al., 2011). To estimate whether the environmental conditions are suitable for the species distribution, the one-class dataset (only presence data) was separated by a hyper-plane having the largest margin from the data (Vapnik, 1995; Reiss et al., 2011).

4. Model Calibration and Validation

Occurrence sites were equally divided into calibration and validation sites by longitude. At first, 88 (44 presence sites and 44 absence sites) occurrence data from the eastern part of Asia were used for calibration. The other 88 (44 presence sites and 44 absence sites) occurrence data from the western part of East Asia were grouped for validation. Further calibration and validation were performed switching data sets for calibration and validation.

Population growth of BPH is dependent on temperature and relative humidity which determine microenvironment of rice field (Somchai and Toshihide, 1993). Temperature is the key variable associated with mortality of BPH during winter season and very humid condition is preferred by BPH (Allsopp and Butler, 1987;

Damos and Savopoulou-Soultani, 2012; Kisimoto and Sogawa, 1995). To examine differences in the spatial distribution of BPH during winter by climate variables, temperature related variables (*TT*) and both temperature and precipitation elated variables (*TP*) were used as inputs, respectively. *TT* includes monthly temperature, minimum temperature of coldest period and mean temperature of coldest quarter. For *TP*, monthly precipitation and precipitation of coldest quarter were added to *TT*.

A series of steps was taken to make ensemble predictions. To predict spatial distribution of BPH overwintering area, climate data during winter season, e.g., December, January and February in northern hemisphere, were used as inputs. Monthly data of temperature and precipitation were paired by hemisphere to represent one of winter months because time periods for winter season differ by hemisphere. For example, temperature data of December and June were paired to represent the first month of winter season in northern and southern hemisphere, respectively. Such pairs of monthly data were combined into a single map. For example, data of December in southern hemisphere were replaced by those of June in the same hemisphere to generate a single surface that contains only winter data. Climate data were obtained from climate surfaces at lower resolution e.g., 10 minutes to represent climate conditions at occurrence sites. Arbitrary sites at which data were replaced with climate data from actual occurrence sites were selected in the Pacific. Instead of actual occurrence sites, these arbitrary sites were used as occurrence sites for calibration of SDMs. The above procedures were automated using a customized C++ software.

Predictions for current climate conditions were performed using five SDMs. Climatic suitability, which ranges from 0 to 1, was calculated on each grid cell. Maps with binary cell value of presence (1) and absence (0), were produced for each SDM using the threshold value of 0.5. The binary maps for each SDM were pooled into a final map to calculate the frequency of agreement between SDMs. For example, a cell with three indicated that three SDMs predicted presence of BPH during winter on the cell.

Climatic suitability in ensemble was dependent on frequency of outcomes from individual ensemble members. For example, a cell in ensemble prediction map was classified to be suitable only when at least three members predicted to be suitable for overwintering of BPH at the cell. Ensemble prediction was denoted by the number of members with identical classification. For example, "En4" represents an ensemble prediction map such that at least four members had the same classification at each cell. The optimum ensemble model, which was selected using the kappa index, was applied to the future predictions.

The kappa index, which is an index for degree of agreement applicable to SDMs, is calculated from a confusion matrix with the number of true positive (a), false positive (*b*), false negative (*c*) and true negative (*d*) cases (Cohen, 1960; Sun, 2011) (Table 1). The kappa value ranges from -1 (complete disagreement) to +1 (perfect agreement) (Cohen, 1960). Kappa statistic (*K*) is calculated as follows:

$$K = \frac{\left(\frac{a+d}{n}\right) - \frac{(a+b)(a+c)+(c+d)(d+b)}{n^2}}{1 - \frac{(a+b)(a+c)+(c+d)(d+b)}{n^2}}$$

where *n* is sum of *a*, *b*, *c*, and *d*.

Table 1. A confusion matrix between species distribution model (SDM) and validation data. *a*, number of cells for which presence was correctly predicted by the model; *b*, number of cells for which the species was not found but the model predicted presence; *c*, number of cells for which the species was found but the model predicted absence; *d*, number of cells for which absence was correctly predicted by the model

		Validation data set	
		Presence	Absence
SDM	Presence	*a*	*b*
	Absence	*c*	*d*

To examine the future geographical distribution of the potential overwintering regions for BPH, five different GCM data were used as inputs to each SDM. Five maps generated for each SDM were averaged by a grid cell to obtain a single map. This single map was converted into a binary map as described previously. Five binary maps for SDMs were used as ensemble members to predict potential overwintering regions of BPH under climate change conditions. A rice yield map at the resolution of 5 minutes was overlaid onto each ensemble map to analyze potential distribution of BPH within rice production area. This map was obtained from http://www.luge.geog.mcgill.ca (Monfreda et al., 2008)

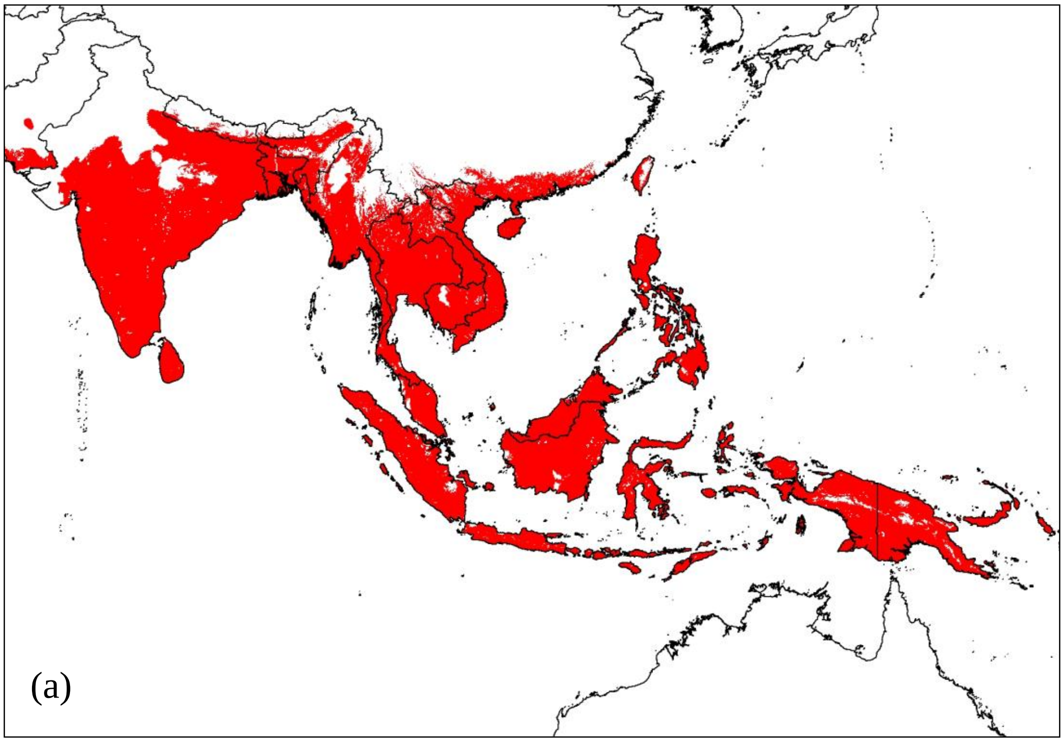
RESULTS

1. Comparison of SDMs under Current Climate Conditions

Overall, BPH overwintering regions predicted from three (ANN, GARP, and SVM) out of five SDMs were similar irrespective of using precipitation variables as inputs (Table 2). Kappa values (*K*) of these SDMs were > 0.95 between outputs using two sets of input variables for each model. BIOCLIM (0.30) and MAXENT (0.59) had low *K* values, between outputs obtained using *TT* (temperature related variables only) and *TP* (both temperature and precipitation variables). For example, BIOCLIM predicted central and northern India, Bangladesh, Myanmar, northern Thailand, most areas in Laos, Cambodia and Vietnam and some cities in the Philippines including Dagupan when *TT* was used as inputs (Fig. 2a). However, these areas were not included in potential overwintering regions of BPH when *TP* was used as inputs to BIOCLIM (Fig. 2b).

Table 2. Kappa statistics between input variable sets of species distribution model (SDM) predictions for distribution of brown planthopper (BPH) overwintering region.

		TP				
		ANN	BIOCLIM	GARP	MAXENT	SVM
	ANN	0.984	-	-	-	-
	BIOCLIM	-	0.296	-	-	-
TT	GARP	-	-	0.954	-	-
	MAXENT	-	-	-	0.589	-
	SVM	-	-	-	-	0.988


(a)

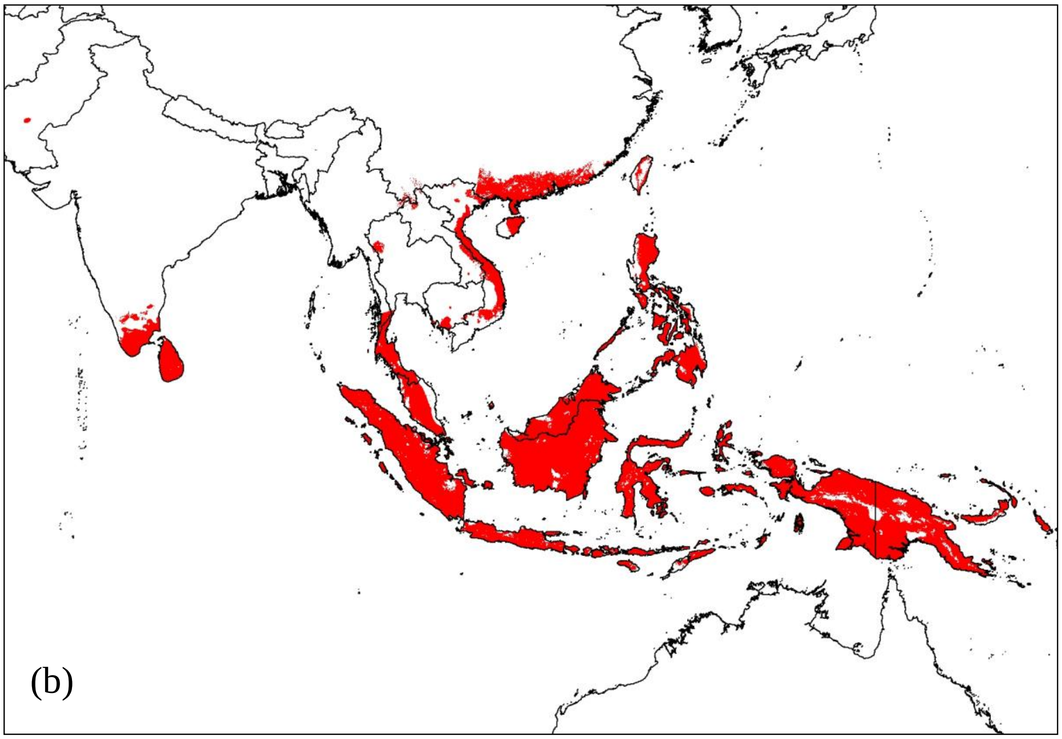


Figure 2. Maps by BIOCLIM using two sets of climatic variables under current climate conditions. Central and northern India, Bangladesh, Myanmar, northern Thailand, most areas in Laos, Cambodia and Vietnam and some cities in the Philippines including Dagupan when *TT* was used as inputs (a) whereas prediction with *TP* did not include (b).

Potential regions of BPH overwintering were similar between ANN, GARP, and SVM for a given set of input variables (Table 3). For *TT*, predicted overwintering regions were consistent among ANN, BIOCLIM, GARP and SVM. MAXENT had different distribution from other SDMs which predicted only small areas in southern China including Guangxi and Guangdong (Fig. 3). For *TP*, distributions of BPH differed by BIOCLIM, MAXENT and other SDMs. For example, ANN, GARP and SVM classified northern Thailand, Myanmar, Laos and Cambodia as potential areas of BPH overwintering whereas BIOCLIM did not include these areas in the predicted distribution (Fig. 4).

Table3. Kappa statistics calculated between a pair of SDMs with each set of input variables.

		TT					*TP*				
		ANN	BIOCLIM	GARP	MAXENT	SVM	ANN	BIOCLIM	GARP	MAXENT	SVM
TT	ANN	-	0.918	0.955	0.027	0.933					
	BIOCLIM		-	0.903	0.028	0.860					
	GARP			-	0.025	0.956					
	MAXENT				-	0.024					
	SVM					-					
TP	ANN						-	0.260	0.968	0.019	0.929
	BIOCLIM							-	0.265	0.108	0.235
	GARP								-	0.018	0.928
	MAXENT									-	0.016
	SVM										-

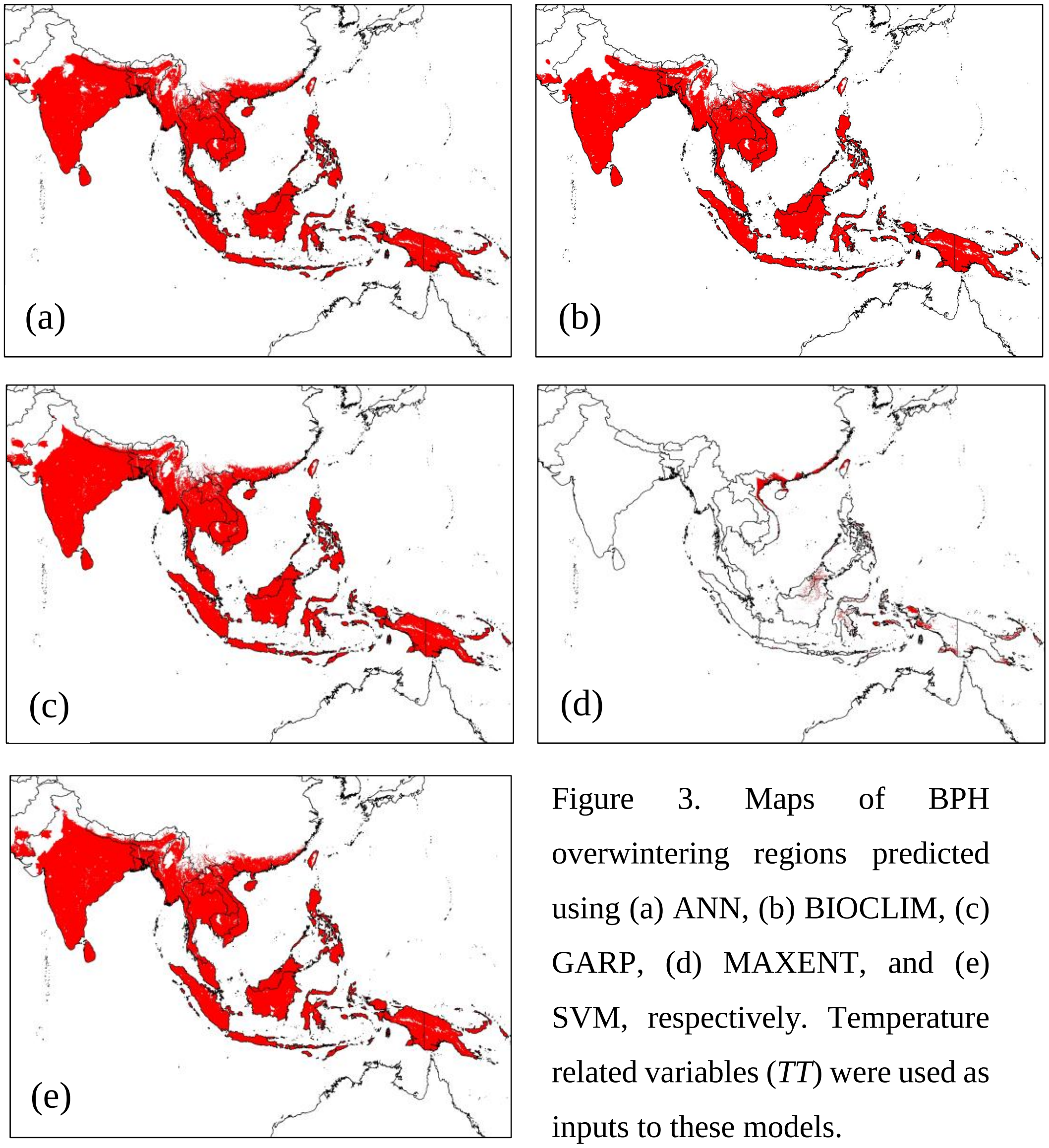


Figure 3. Maps of BPH overwintering regions predicted using (a) ANN, (b) BIOCLIM, (c) GARP, (d) MAXENT, and (e) SVM, respectively. Temperature related variables (*TT*) were used as inputs to these models.

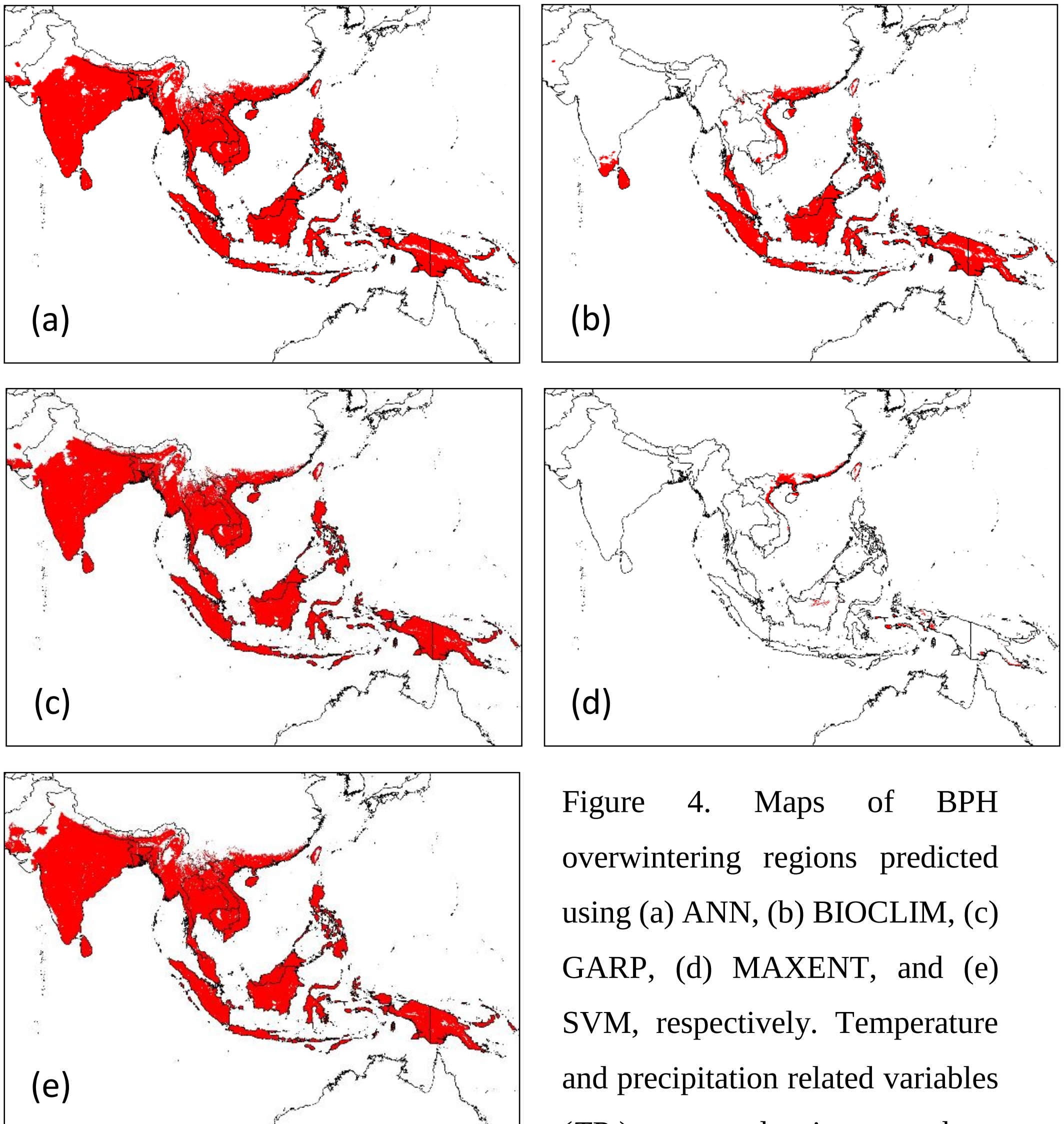


Figure 4. Maps of BPH overwintering regions predicted using (a) ANN, (b) BIOCLIM, (c) GARP, (d) MAXENT, and (e) SVM, respectively. Temperature and precipitation related variables (*TP*) were used as inputs to these models.

2. Validation of SDMs under Current Climate Conditions

All models except MAXENT had considerably high *K* values between model prediction and validation sites when *TT* was used as inputs (Table 4). For example, MAXENT had *K* value about 0.09 whereas other models had *K* values about 0.95. For *TP*, the validation site was most explained by GARP. For example, *K* value of predicted distribution by GARP was greater than that of ANN (0.95) and SVM (0.95). MAXENT (0.07) had lower *K* than did BIOCLIM (0.44).

An ensemble of which at least three members had the same outcomes at a grid cell (En3) with *TP* was selected as the optimum approach to predict potential overwintering region of BPH (Fig. 5). In ensembles of SDMs using *TT* as input variables, *K* values were close to 0.95 and 0.09, for both En3 and En4, and En5, respectively. When *TP* was used, En3 had greater *K* value (0.98) than other ensemble models had, 0.47 and 0.05 for En4 and En5, respectively. The predicted distribution of BPH overwintering areas from En3 with *TP* included Trichur in southern India, Longan in Guangxi in China and Naha in Japan (Dick V.A. and Thomas B., 1979; Otuka et al., 2005b; Otuka 2008).

Table 4. Kappa statistics between SDM and validation sites

SDMs	Species Data needed for model calibration	*TT*	*TP*
ANN	PA[a]	0.95	0.95
BIOCLIM	P[b]	0.95	0.44
GARP	PA	0.95	0.98
MAXENT	P	0.09	0.07
SVM	PA	0.95	0.95
En3	-	0.95	0.98
En4	-	0.95	0.47
En5	-	0.09	0.05

[a] Presence and absence data

[b] Presence data

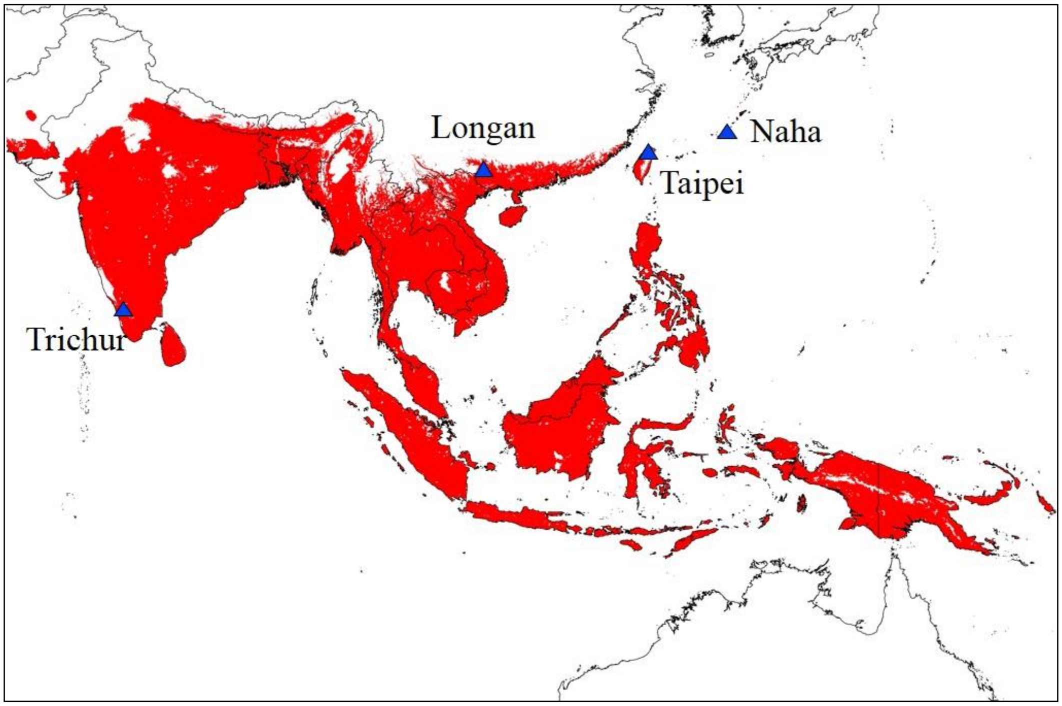


Figure 5. Map of potential overwintering area for BPH under current conditions using En3 with *TP*.

3. Future Potential Range Shift

Potential overwintering areas of BPH under future climate conditions were different from the distribution under current climate condition using En3 with *TP*. The distribution in the northern hemisphere gradually extended to north in most areas in 2020s and 2050s. Overall, the northern limit of BPH overwintering increased by 1 - 2° (~100 – 200Km) in 2050s compared with that under current conditions. In southern hemisphere, potential overwintering regions of BPH were similar between current and future conditions.

The greatest shift was predicted in areas between India and Pakistan (Fig. 6). For example, under the current conditions, BPH was predicted to overwinter in Tandamaidas where is upper region of New Delhi in India (29.62°N, 78.47°E). Overwintering regions of BPH were expanded to Pargamal in India (32.78°N, 74.56°E) and Tata Pani in Pakistan (33.62°N, 73.96°E) in 2020s and 2050s, respectively. In 2050s, the limit of potential BPH overwintering area in the northern boundary of India, Tulsipur (27.53°N), would shift upward to Bhagawati in mid-western Nepal (28.96°N) at the same longitude 82.45°E. Under the future climate conditions of both 2020s and 2050s, predictions classified Bikaner (28.01°N, 73.32°E), Gwalior (26.21°N, 78.18°E) and Jabalpur (23.17°N, 79.95°E) as potential BPH overwintering areas which were not included in predictions under current conditions.

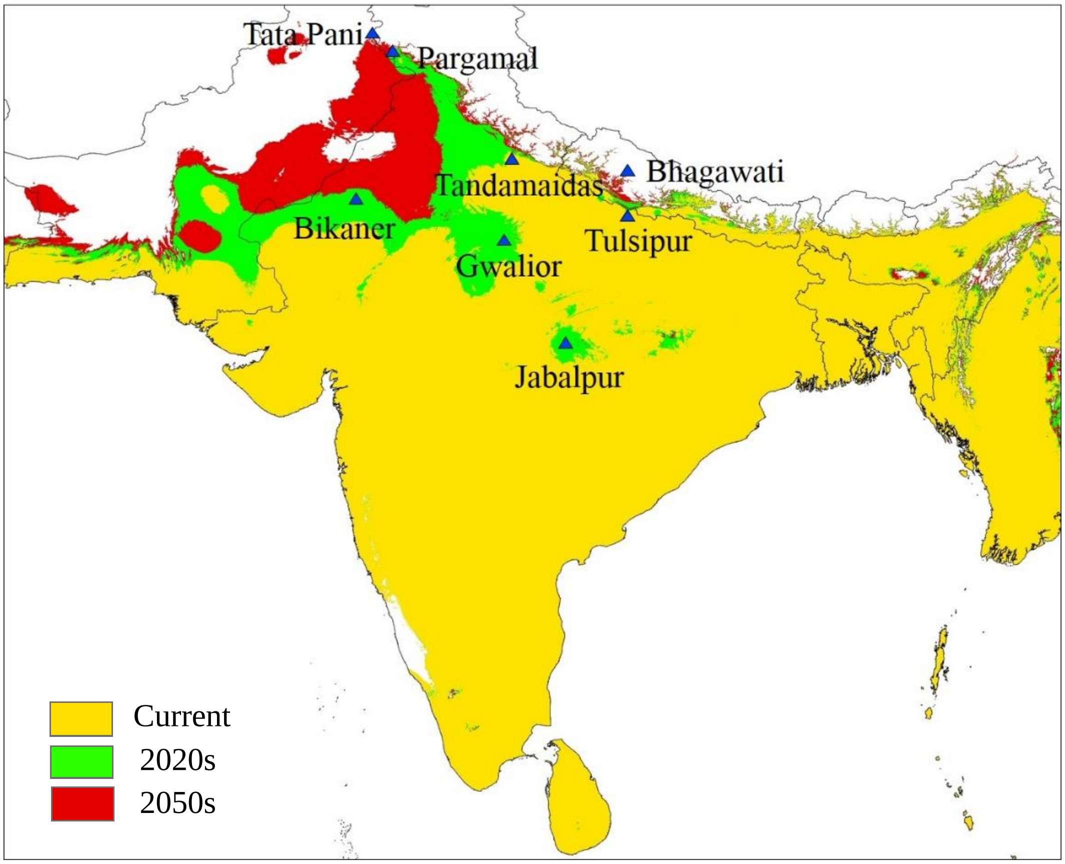


Figure 6. Map of BPH potential overwintering area in India.

Latitudinal shift in BPH overwintering areas was noticeable in Myanmar and southern China (Fig. 7). For example, in Guangxi province, the lower part of Liuzhou (24.20°N, 109.31°E) was predicted as potential overwintering region under the climate conditions in 2020s which was not included in predictions under the current conditions. In 2050s, the latitudinal limit progressively extended up to near Guilin (25.17°N, 109.35°E) from Liuzhou. In eastern Myanmar, shifts in potential distribution had considerably high spatial variations between current and future climate conditions. For example, Nawngmun (27.51°N, 97.81°E), Lashio (22.95°N, 97.75°E), and Pindaya (96.68°N, 20.96°E) were additionally included in predictions with future climate conditions.

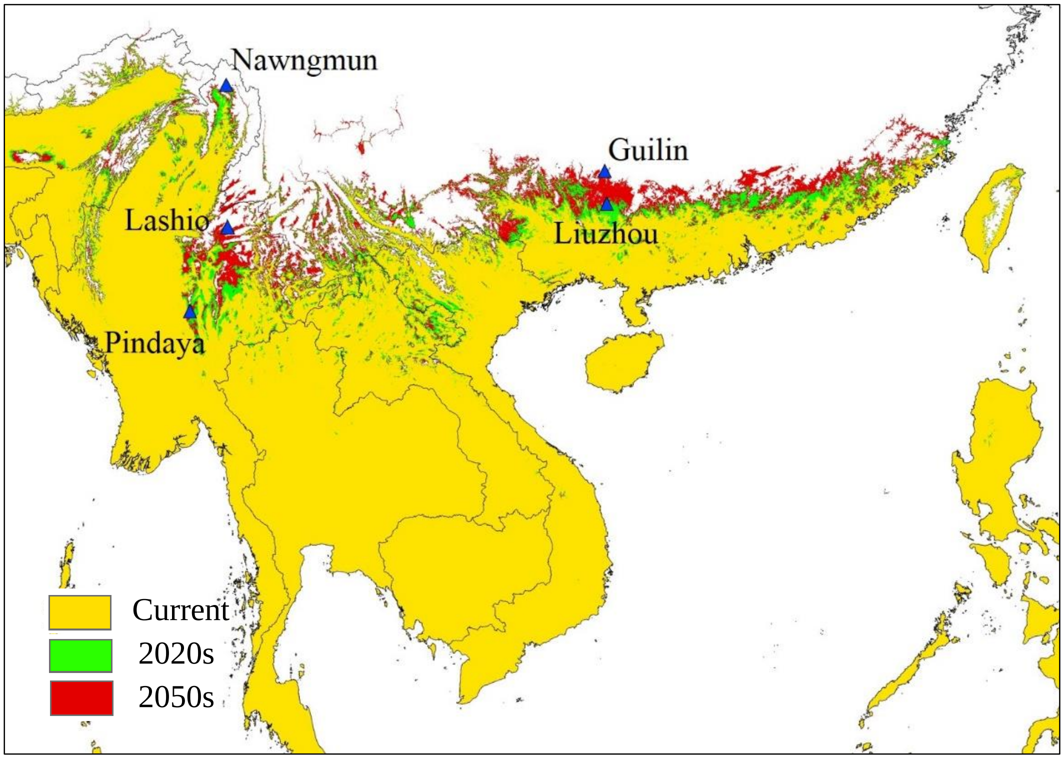


Figure 7. Map of BPH potential overwintering area in China

In Japan, the northernmost boundary of potential range for BPH overwintering shifted by 100 Km in 2050s (Fig. 8). For example, the southernmost region of Kumage district (30.25°N, 130.48°E) was predicted as the most upper region of potential overwintering area of BPH in current day. However, BPH was predicted to overwinter in the southern region of Tanegashima Island (30.50°N, 130.91°E) and the small region in Kimotsuki where is the southernmost area of Kyushu (31.04°N, 130.71°E) in 2020s and 2050s, respectively.

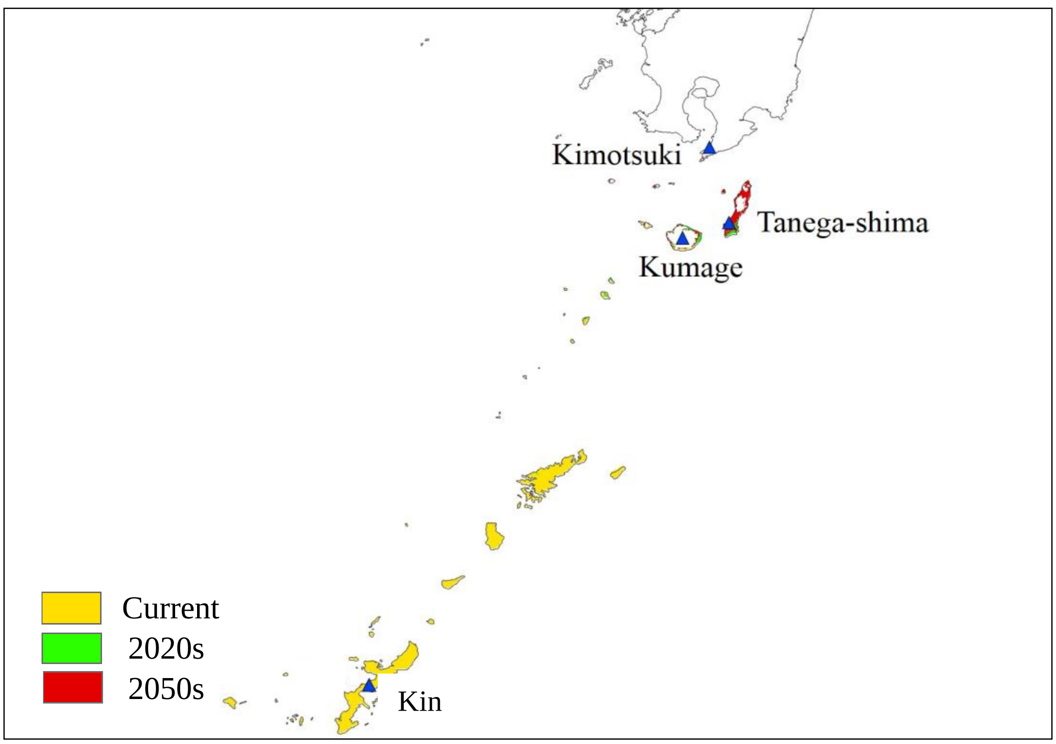


Figure 8. Map of BPH potential overwintering area in Japan

DISCUSSION

Overall, predicted BPH overwintering area under current climate condition was consistent with the previously reported regions, e.g., Taipei in the northern part of Taiwan and Naha in Okinawa in Japan (Chu and Yang, 1985; Otuka et al., 2005b). Under climate changes, it was projected that potential BPH overwintering area in East Asia where rice is mostly cultivated would increase the risk of BPH. The northern limit of BPH overwintering suitability shifted north until 2050s. For example, in the southern China, potential overwintering region of BPH expanded by 100 - 200 Km in the next 40 years. It has been suggested that climate change would cause expansion or upward shift in overwintering region of an insect species (Pelini et al., 2009; Bale and Hayward, 2010). Under future climate conditions, changes in geographical suitability of BPH overwintering would affect rice production. Because migration sources of BPH are dependent on the overwintering areas, it is expected that dispersal pattern of BPH would also change. Accordingly, new agricultural management for rice cropping, e.g., timing of transplanting and use of pesticides should be adopted under future conditions.

Geographical changes in overwintering area under future climate would influence the time and the routes of BPH migration. Future changes in temperature and precipitation may cause migration in early season if climate conditions are suitable for BPH to take off, e.g., air temperature of 17 ℃ in early season (Mochida, O 1979). Under current climate conditions, the immigration period is normally from June (Turner et al., 1999). Climate change would cause BPH to arrive north-eastern China, Korea and Japan from the southern China in the early season, e.g., April or May. Outbreak region of BPH would differ in the future because BPH have different migration route depending on the migration source areas and wind pattern (Zhu, 2000). For example, northern Vietnam which is the current BPH migration source of China may shift upward in 2050s, e.g., near Guizhou in southern China (Otuka et al., 2008). This suggests that prediction of BPH trajectories from new sources merits further studies.

Our results suggested that more damages in rice production would be incurred by BPH outbreaks in Japan under climate changes. It was predicted that the southernmost of Kumage district (30.25°N, 130.48°E) would be possible for BPH to overwinter under current conditions although occurrence site of Kin in Okinawa (26.45°N, 127.93°E) was used as the northern limit reported data for BPH overwintering in our study (Otuka et al., 2005b). It was predicted that overwintering area of BPH included Kimotsuki (31.04°N, 130.71°E) which is the southernmost part of Kyushu Island as well as Kin in 2050s. Kimotsuki where BPH can overwinter in future conditions is about 580 Km distant from Kin. BPH that overwinters in the southern Kyushu Island would migrate into other major rice production areas in Japan more frequently in 2050s. This could damages rice in early stage which is more vulnerable to BPH invasion than the rice already developed (Kisimoto and Sogawa, 1995).

Ensemble approach contributed to minimize the model uncertainty to predict potential areas of BPH overwintering. The SDM which had the highest *K* value varied by the set of input variables. For example, GARP had the highest *K* value when TP was used as inputs. On the other hand, ANN, BIOCLIM, GARP, and SVM had the same *K* values, which was the highest value when TT was used as inputs. Therefore, it is recommended to use ensemble method for distribution modeling of a species.

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미래 기후 조건에서의 벼멸구 월동 가능지 앙상블 예측

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초록 (ABSTRACT IN KOREAN)

벼의 주요 해충인 벼멸구 (*Nilaparvata lugens* Stål)는 중국이나 베트남과 같은 동남아시아 지역에서 월동을 하고, 봄철이나 여름철에 한국과 일본을 비롯한 온대지역으로 비래한다. 기후변화로 인한 벼멸구의

잠재적인 월동지역의 변화는 비래 시기, 기원지, 경로에도 상당한 영향을 미칠 수 있다. 본 연구에서는 주어진 기후조건하에서 다양한 생물 종의 분포를 예측하는 5 종의 종 분포 알고리즘을 사용하여 벼멸구의 월동 가능지역을 예측하였다. 미래의 월동 가능지 예측에 있어 개별적인 공간 분포 모델을 사용하는 것은 불확실성이 크기 때문에, 개별 모델 중 예측력이 우수한 알고리즘을 파악하고 미래 기후 조건에서의 예측력을 향상시키기 위해 앙상블 방식을 적용한 결과를 분석하였다. 문헌으로 발표된 벼멸구의 월동 가능 지점들과 현재 기후 조건을 나타내는 1 Km 고해상도 월별 기후 자료를 사용하여 공간 분포 모델의 파라미터들을 설정하고 검증하였다. 미래 기후 조건을 대표하기 위해 5 개의 기후모델 자료를 기반으로 생산된 월별 고해상도 기후변화 자료를 사용한 분석결과 2050 년대에는 현재 월동 가능지역 보다 100-200 Km 정도 위도가 북상할 것으로 예측되었다. 이러한 결과로 미루어 볼 때, 벼멸구가 현재보다 이른 시기에 온대지역으로 비래하여 피해를 입힐 것으로 전망된다. 본 연구는 벼멸구의 월동 가능 지역을 예측함으로써 향후 벼 작물 보호를 위한 대책 마련 및 정책 수립을 위한 기초자료로 활용될 수 있다.